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LIFE CYCLE SUSTAINABILITY ASSESSMENT

Accounting for spatial variability in life cycle cost-effectiveness assessments of environmental impact abatement measures

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Abstract

Purpose The environmental and economic impacts of livestock production systems are typically assessed using global characterisation factors and data, even though several impact categories call for site-specific assessments. Here, we account for spatial variability by addressing potential interactions between geographic locality and the cost-effectiveness of farm investments that aim to reduce system environmental impact, using Danish pig production as a case-in-point.

Methods An LCA-based, spatially explicit environmental abatement cost framework was developed to assess the cost-effectiveness of potential environmental abatement strategies. The framework was tested for Danish pig production in a "4 manure management × 4 geographic location" scenario analysis design. In addition to the baseline, the alternative manure management strategies were on-farm anaerobic digestion, slurry acidification and screw press slurry separation, implemented in an integrated pig farming system. The geographic locations differed in their proximity to Natura 2000 areas and in pig farming density. Eight different impact categories were assessed through an LCA using spatially explicit characterisation factors whenever possible, and annualised abatement potential was estimated for each manure management scenario and in each geographic location. We also estimated the financial performance for each scenario, through a discounted cash flow analysis at a whole-farm level.

Results and discussion We observed significant interactions between geographic location and system environmental and economic performance under baseline conditions. Significant location effects were also observed for the cost-effectiveness of all manure management strategies tested. Anaerobic digestion was the only "*win–win*" strategy that increased farm profits while reducing system environmental impact in two of the geographic cases: when implemented in a region of high pig farming density located near Natura 2000 and when implemented in a region of high pig farming density located far from Natura 2000 areas. Slurry acidification and slurry separation achieved sizeable abatement potential for impacts on ecosystem quality but incurred large additional costs in all geographic case studies considered, particularly when arable land was limited near the pig farm.

Conclusions Accounting for basic spatial characteristics within an environmental abatement cost framework had significant impact on the cost-effectiveness of on-farm investments for mitigation of system environmental impact. To the best of our knowledge, no studies to date have utilised such spatial characteristics within environmental abatement cost modelling of livestock farming systems. The presented framework has the potential to be further expanded using more detailed spatial, economic and geophysical data, which could ultimately improve decision-making regarding cost-effective investments that aim to improve the sustainability of livestock farming operations.

Keywords Cost-effectiveness · Geographic information system · Life cycle assessment · Manure management · Pig production · Spatial variability

1 Introduction

Life cycle assessment (LCA) models have been commonly used to evaluate potential environmental impacts associated with the operation of livestock systems, by assessing nutrient flows through the farming system as a whole. These

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assessments typically use generic, global emission characterisation factors (Guinée and Lindeijer 2002); however, the importance and relevance of these impact categories can be significantly affected by spatial variability (e.g. topography, soil type, precipitation) (Basset-Mens et al. 2006; Potting et al. 2006; Roy et al. 2014a). Failure to account for such uncertainties can lead to inaccurate and misleading estimates of potential impacts (Azevedo et al. 2013), particularly when comparing the effectiveness of potential farm investments that aim to reduce system environmental impact (Pexas et al. 2020a).

Recent major projects like the IMPACT World + (http://www.impactworldplus.org) (Bulle et al. 2019) have attempted to provide spatially explicit characterisation factors on a global scale, mainly for the assessment of eutrophication potential, acidification potential, land use and water footprint (water scarcity) associated with specific nitrogen and phosphorus emissions. Other studies have proposed ways to integrate geographic information system tools (GIS) in LCA to account for the effect of spatial differentiation on pollutant transportation and fate (Azevedo et al. 2013; Henryson et al. 2018).

In addition to environmental implications, geography can also affect the economic performance of pig production systems. Variability in feed, fuel and construction material prices across the spatial dimension can result in large variations in on-farm operating costs. Regulations and restrictions imposed by regionalised policies for environmental pollution mitigation (i.e. Nitrates Directive, Water Framework Directive) can cause significant increases in slurry transportation costs and may require additional farm investments for manure treatment (Fealy and Schröder, 2008; Jacobsen et al. 2019). Pig farm density at regional level can affect the feasibility and cost-effectiveness of potential farm investments (e.g. anaerobic digestion) through agglomeration effects, including knowledge and input sharing, and specialised labour supply that can improve farm technical efficiency and profitability (Cohen and Paul 2005; Larue et al. 2011). Therefore, it is necessary that the potential geographic variability of economic parameters is addressed whenever possible, particularly when cost-effectiveness assessments are used to guide decision-making regarding strategies that aim to improve system sustainability and shape policies on a broader spatial scale (Ciroth et al. 2002; Pexas et al. 2020b).

Pig production in Denmark was utilised as a case-in-point to investigate the potential for integration of spatial data in methods that facilitate decision-making for environmental abatement strategies. Pig production is regarded among the largest contributors to acidification of ecosystems and eutrophication of freshwater bodies arising from livestock, and Denmark is the world's largest pork meat exporter (De Vries and De Boer 2010). Danish pig production primarily occurs in Jutland, an area of relative topographic and climatic homogeneity (Larue et al. 2007). However, a large part of this land is covered by nature-sensitive areas designated to protect various species and habitats (i.e. Natura 2000 areas) (Jacobsen et al. 2019). Moreover, the country is characterised by large regional variability in pig production intensity (Larue et al. 2007).

The specific aim of this study was to develop a spatially explicit, environmental abatement cost framework to assess and compare the cost-effectiveness of alternative manure management strategies that aim to reduce the environmental impact of pig farming systems, when implemented in a range of geographic case studies. In doing so, we investigated differences in system environmental performance across different locations for several potential impact categories, using spatially explicit environmental impact characterisation factors. Additionally, we evaluated effects of topographic variability on the economy of the system by accounting for variations in manure transportation and application regimes associated with the implementation of each manure management strategy.

2 Methods

A bottom-up, technology-based, environmental abatement cost approach was followed and integrated with spatial information to achieve the goal of this study. The analyses were carried out through the following steps:

i. We described the operation of one pig farming system with the implementation of four different manure management strategies, the baseline and three alternatives that target reductions in system environmental impact.
ii. We developed scenarios to simulate the operation of the pig production system with the implementation of the above manure management strategies in four different locations across our study area.
iii. We designed a 4 × 4 scenario analysis to estimate the annualised system environmental impact for a range of impact categories, through a spatially explicit environmental LCA framework.
iv. We used the same scenario analysis design to estimate whole-farm annualised financial performance metrics derived from a discounted cash flow analysis over a 25-year time horizon.
v. Finally, we assessed the cost-effectiveness of each manure management strategy in reducing system environmental impact and evaluated the effect of spatial variability on it.

2.1 Goal and scope of environmental life cycle assessment

A cradle-to farm gate, life cycle impact assessment framework was developed in SimaPro 8.5.0.0 (PRé Consultants, Amersfoort, The Netherlands) according to Pexas et al. (2020b). The goal of the framework was to simulate the operation of the typical Danish integrated pig farming system, under baseline manure management conditions and with each of the alternative manure management strategies implemented.

Within the system boundaries (Fig. 1), we modelled (i) feed production (i.e. diet formulations used), (ii) animal growth at pig barn across the four production stages and (iii) manure management at pig barn, storage and field. The functional unit of the analysis was the production of 1 kg of live weight pig at slaughter weight adjusted for mortality rates. This functional unit was selected as it facilitates intuitive understanding of the specific outputs in relation to on-farm operations. Environmental LCA outputs were initially estimated according to the functional unit, and then scaled to the annualised system production to meet the requirements for economic modelling of the pig farming system (Sect. 2.5).

System expansion was used to avoid co-product allocation. When this was not possible, economic allocation was used (Weidema and Schmidt 2010; Mackenzie et al. 2017).

2.2 LCI

2.2.1 Pig farming system description

Analyses were performed on a typical, integrated Danish pig farming system, which reared pigs that were offspring of Danish Landrace × Yorkshire sows and Duroc sires (Pexas

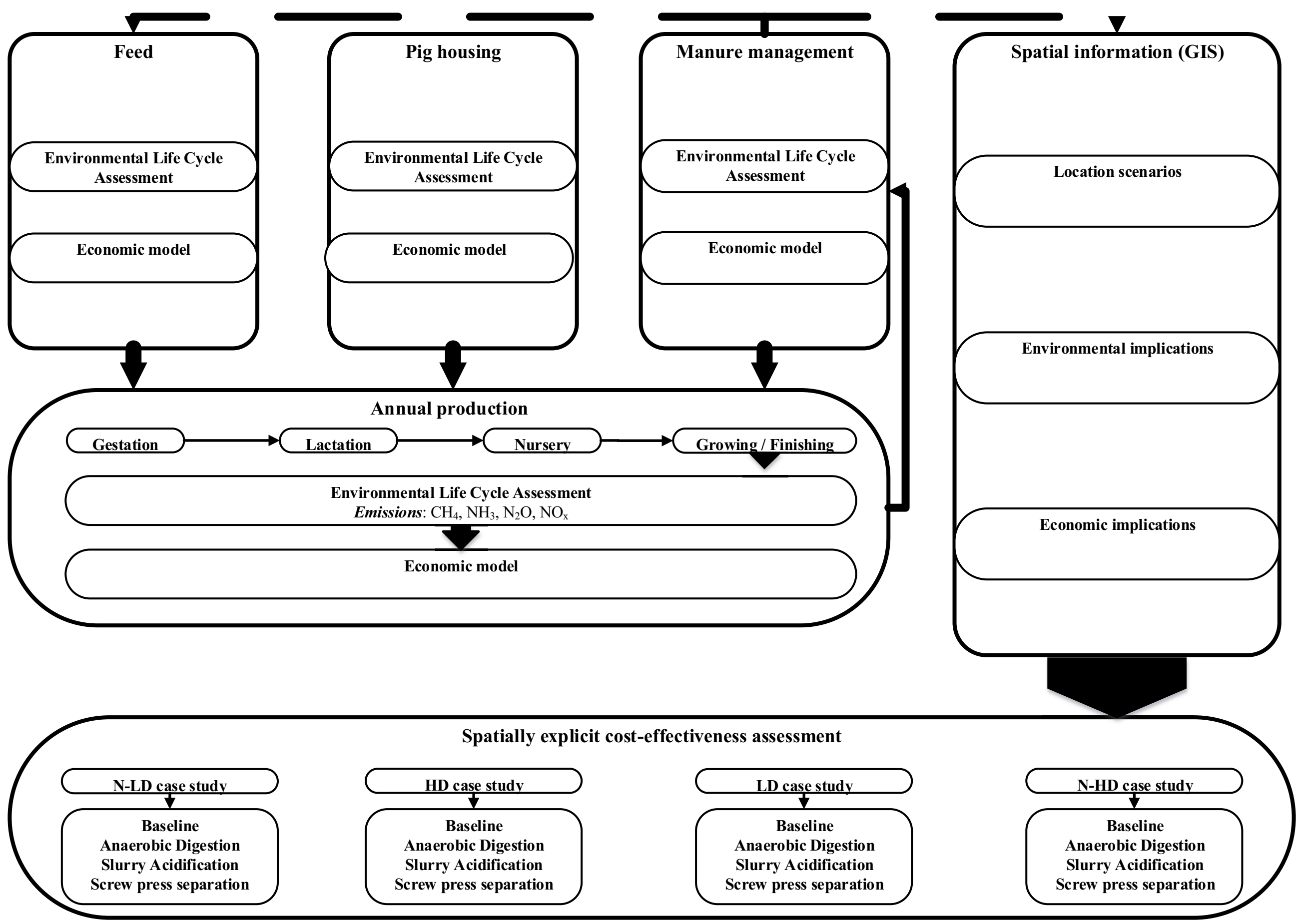


Fig. 1 Main components and flows within the system boundaries of the spatially explicit cost-effectiveness analysis. Solid arrows represent connections between the individual environmental, economic and spatial frameworks. Dashed arrows illustrate discounts in synthetic fertiliser for crop production and that manure application regimes provide context for the spatial analysis. We considered energy use (electricity, natural gas, diesel fuel) in all relevant processes within the system boundaries. GIS geographic information systems, N-LD case study less than 400 m from Natura 2000 and in region of 2–3 pig farms per hectare, N-HD case study less than 400 m from Natura 2000 and in region of 7–9 pig farms per hectare, LD case study further than 2 km from Natura 2000 and in region of 2–3 pig farms per hectare, HD case study further than 2 km from Natura 2000 and in region of 7–9 pig farms per hectare

et al. 2020b). The production system comprised four distinct stages: (i) gestation (gestating sows), (ii) lactation (lactating sows and suckling piglets), (iii) nursery (weaners < 30 kg) and (iv) growing/finishing (pigs reared until slaughter weight and replacement gilts). It followed a 3-week batch farrowing system and produced approximately 13,100 slaughter pigs annually at 110 kg slaughter weight. For each production stage, the pig housing system consisted of an indoor, mechanically ventilated building that complied with the best available techniques (BAT) guidelines for rearing of pigs (Santonja et al. 2017). We considered the use of six different diet formulations across the four production stages: gestating sow diet, lactating sow diet, nursery diet from 6.7 kg to 15 kg, nursery diet from 15 to 30 kg, growing diet from 30 to 65 kg and finishing diet from 65 to 110 kg—slaughter weight (Tybirk et al. 2016). Potential environmental impacts associated with the production of individual feed ingredients and the preparation of diet formulations were considered in the analysis (Pexas et al. 2020b).

Methane (CH_4) emissions and nutrient excretion (N, P, K) associated with animal growth within the pig farming system were calculated following the mass balance principle, tracing nutrient flows throughout the production stages. The effects of ambient temperature on indoor climate parameters, energy consumption for climate control and methane (CH_4), ammonia (NH_3), nitrous oxide (NO_x) and dinitrogen monoxide (N_2O) emissions were also accounted for in the description of the system (Pexas et al. 2020b). We used the same approach to model CH_4, NH_3, NO_x, N_2O and atmospheric nitrogen (N_2) emissions from slurry at pig housing (pen and slurry pits), slurry storage and field application. Specific emission factors for chemical substances associated with the operation of the production system were obtained by IPCC guidelines (Dong et al. 2006), the IMPACT World + project (Bulle et al. 2019) and relevant literature (Nguyen et al. 2011; Pexas et al. 2020b).

Agri-footprint and Agribalyse v1.3 were primarily used to model the feed production component, and the Ecoinvent 3 database was used for processes related to pig housing and manure management (Colomb et al. 2013; Vellinga et al. 2013; AGRIBALYSE 2016; Wernet et al. 2016; Agri-footprint 2017). Section 2 of the Electronic Supplementary Material provides a detailed description of the life cycle inventory (LCI) used for the development of the typical, integrated Danish pig farming system.

2.2.2 Manure management strategies

i. Baseline practice

Under baseline conditions, manure was stored outside in concrete, covered slurry tanks and applied by trail-hose tanker to replace synthetic fertiliser for crop production. To estimate the amount of manure applied as organic fertiliser, we used a 75% nutrient substitution rate for nitrogen, 97% for phosphorus and 100% for potassium (Nguyen et al. 2011).

In addition to the baseline scenario, we modelled the system with the implementation of the three most commonly adopted alternative manure management strategies with potential to reduce the environmental impact of pig farming systems (Ten Hoeve et al. 2014; Pexas et al. 2020a).

ii. Anaerobic digestion (AD)

For this scenario, we simulated the co-digestion of pig slurry with grass silage (80:20 w/ w) on-farm, for biogas production. Electricity and heat was generated by the biomethane yield at a combined heat and power plant (CHP) that operated at 80% efficiency and was discounted from on-farm energy use. Upon treatment, the nutrient-enriched digestate was applied in the fields under baseline conditions (trail-hose tanker) but with an increased fertiliser efficiency; substitution rates were for N: 85% and P: 100% (Vega et al. 2014).

iii. Slurry acidification (Acid)

Slurry acidification was simulated as an automated process that took place in an acidification plant adjacent to the pig housing facilities. During the treatment phase, slurry was pumped from the pits to the plant where it was acidified, mixed and then pumped back to the slurry pits. The acidified slurry was stored and applied under baseline conditions (Kai et al. 2008; Fangueiro et al. 2015). For this manure management strategy, 9.7 kg of highly concentrated sulphuric acid (96% H_2SO_4) and 15 kg of calcium carbonate ($CaCO_3$) per tonne of slurry were required, as well as an additional 3 kWh per m^3 of slurry acidified of energy required for the mixing (Ten Hoeve et al. 2016).

iv. Screw press separation (SP)

The separation of slurry by screw press was simulated as a process that occurred at manure storage. Upon separation, the liquid fraction was stored and applied under baseline conditions. The solid fraction was piled on-farm and applied by broadcast spreading and rapid incorporation. The substitution rate for N was different for the two fractions with N_{liquid} at 75% and N_{solid} at 65% (Ten Hoeve et al. 2014).

The specific emission factors associated with each of the alternative manure management scenarios above is presented in Sect. 2.1.2 of the Electronic Supplementary Material.

2.3 Geographic case studies and spatial analysis

Four location scenarios were developed to account for spatial variability in environmental and economic impact associated with the operation of the pig production system, as well as to address potential effects of spatial differentiation on the cost-effectiveness of the alternative manure management strategies.

Aside from addressing topographic variability through spatially explicit characterisation factors, we also considered the following two spatial parameters for the development of the four geographic case studies: (i) proximity of pig farm to nature sensitive areas (Natura 2000 network) and (ii) pig farming density at municipality level. If a pig farm was located closer than 400 m from a Natura 2000 area, we considered it to be 'at close proximity' to nature-sensitive areas (Jacobsen et al. 2019). We evaluated the 'distance from Natura 2000 areas' criterion by performing a buffer analysis for Natura 2000 areas contained within the extent of Danish administrative boundaries.

We identified spatial zones in Jutland, Denmark, that meet each possible combination of the spatial criteria above and selected randomly four locations within them, to provide context for the spatially explicit environmental abatement cost analysis (Fig. 2a, b):

i. '*N-LD*': located at 57° 4.0669 N, 9° 44.7008 E, characterised by close proximity to Natura 2000 areas (< 400 m) and in a region of 2–3 pig farms per hectare.
ii. '*N-HD*': located at 56° 41.6027 N, 8° 38.1546 E, characterised by close proximity to Natura 2000 areas (< 400 m) and in a region of 7–9 pig farms per hectare.
iii. '*LD*': located at 56° 19.4616 N, 10° 41.7729 E, at a distance from Natura 2000 areas (> 2 km) and in a region of 2–3 pig farms per hectare.
iv. '*HD*': located at 54° 57.057 N, 9° 56.378 E, at a distance from Natura 2000 areas (> 2 km) and in a region of 7–9 pig farms per hectare.

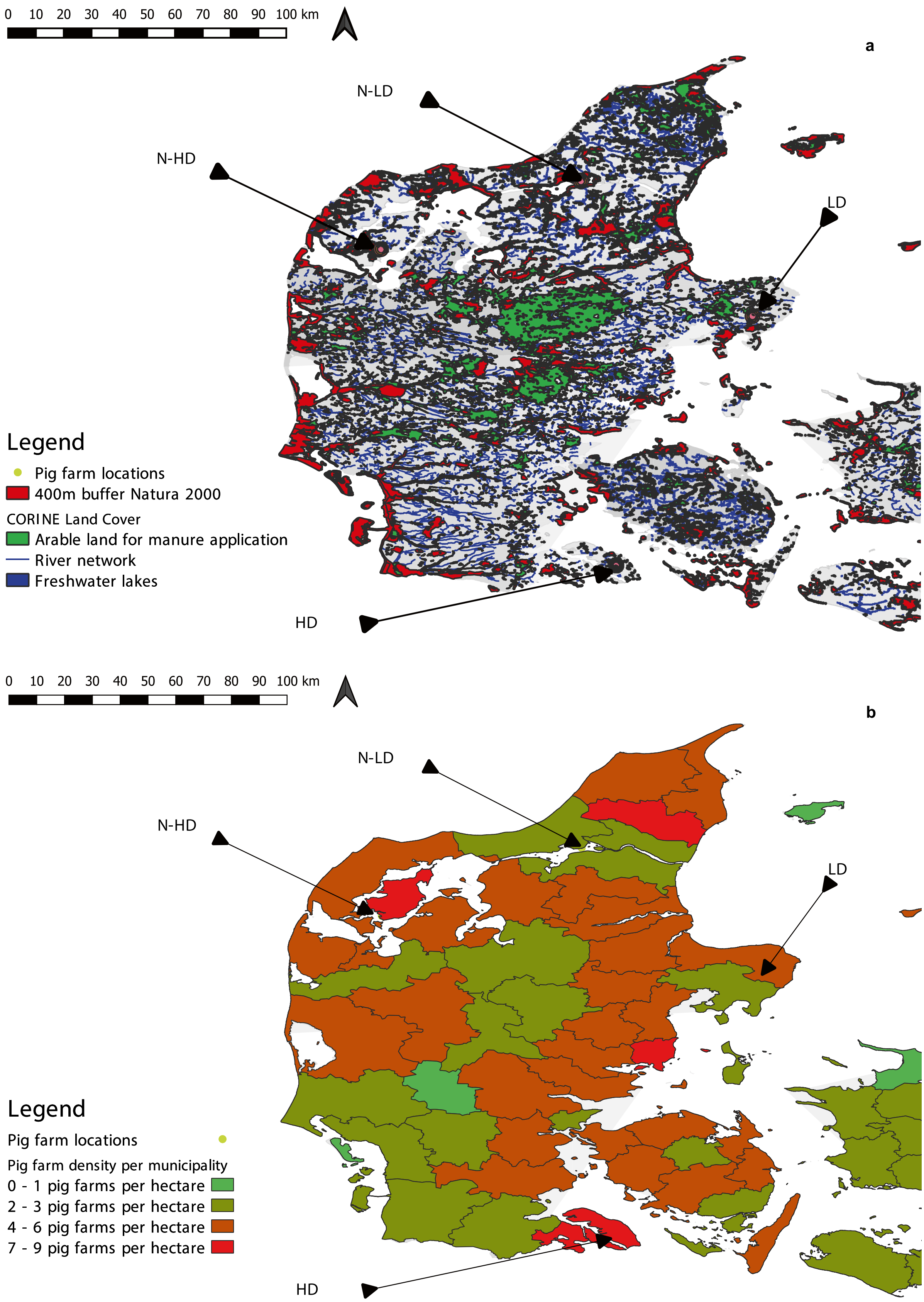
For each of the above case studies, we performed a radial analysis using 1 km increments and the farm coordinates as the geocentre, to determine the availability of arable land for manure application in areas surrounding the farm. We estimated the required transportation distance for manure to be applied in arable land according to the Danish Regulation of Nutrients in Agriculture & the Danish Nitrates Action Programme, which specifies an allowance of 170 kg N ha^{-1} year^{-1} and a ceiling of 35 kg P ha^{-1} year^{-1} (Ministry of Environment and Food of Denmark 2017).

According to Danish Environmental Agency, the maximum allowance for nitrogen deposition in ammonia sensitive habitats such as Natura 2000 areas is below 0.2 kg ha^{-1} year^{-1} per pig farm in cases where more than one neighbouring farms are located within 1 km radius from the system under assessment. If there are no neighbours within the 1-km radius, then the maximum allowance is below 0.7 kg ha^{-1} year^{-1} per pig farm. The neighbouring distance depends on the size of the farms. In this study, we assumed the neighbouring farms would be of the same size, 500-sow integrated pig farming systems, which corresponds to the 1-km distance threshold (Jacobsen and Ståhl 2018; Jacobsen et al. 2019). Therefore, for regions with 7–9 pig farms per hectare (cases HD and N-HD) we assumed the lower maximum allowance and that the available arable land would be shared between at least three pig farms, while for regions with 2–3 pig farms ha^{-1}, we assumed the higher allowance and no neighbours to share land for manure application. Such variability in manure application related factors could have implications in system environmental and economic performance, particularly when evaluating the cost-effectiveness of strategies that directly affect manure composition.

Spatial analysis was performed in QGIS 3.10.9 'A Coruña' (QGIS.org 2020), with data obtained from the European Environmental Agency (EEA, available at https://www.eea.europa.eu/data-and-maps/data/natura-11/natura-2000-spatial-data) and CORINE Land Cover 2018 (Coordination of Information of the Environment, available at https://www.copernicus.eu/en). Pig farm density data were obtained from the Danish Statistics Agency (Statbank Denmark, available at www.statbank.dk/BDF51).

2.4 Environmental LCIA

The annualised environmental impact of the pig production system was calculated as the summation of the equally weighted environmental impacts for each production stage within the cradle-to-farm gate system boundaries. The environmental impact categories assessed were chosen based on FAO guidelines for the environmental impact assessment of pig supply chains (FAO 2018a) and the FAO guidelines for water use in livestock production (FAO 2018b). To account for spatial variability in system environmental impact across different geographic case studies, we adapted the IMPACT 2002 + v2.14 and ReCiPe 2016 Midpoint v1.01 impact calculation methods by using spatially explicit factors from the IMPACT World + project (Bulle et al. 2019) (Table 1). The specific impact categories were *aquatic acidification potential* (AAP) and *terrestrial acidification potential* (TAP) expressed in tonnes of sulphate (SO_2^-) equivalents, *marine eutrophication potential* (MEP) expressed in kg of nitrogen (N) equivalents and *freshwater eutrophication potential* (FEP) expressed in tonnes of phosphate (PO_4^{3-}) equivalents. System water footprint was also estimated using spatially explicit characterisation factors through the *available water resources* (AWARE v1.01) method expressed in cubic meters of water used (m^3). The spatially explicit characterisation factors used in this study take into account soil-specific factors that affect pollutant transportation and deposition. These factors include estimates of the soil solution H + concentration transferred via surface waters,


0 10 20 30 40 50 60 70 80 90 100 km
a
N-LD
N-HD
LD
HD
Legend
Pig farm locations
400m buffer Natura 2000
CORINE Land Cover
Arable land for manure application
River network
Freshwater lakes
0 10 20 30 40 50 60 70 80 90 100 km
b
N-LD
N-HD
LD
HD
Legend
Pig farm locations
Pig farm density per municipality
0 - 1 pig farms per hectare
2 - 3 pig farms per hectare
4 - 6 pig farms per hectare
7 - 9 pig farms per hectare

◂**Fig. 2** Four pig farm locations in Jutland, Denmark. The top map presents areas within the Danish administrative boundaries covered by arable land and Natura 2000 protected areas (including 400 m buffer); freshwater lakes and the Danish river network are also included. The bottom map presents pig farm density at a municipality level. *N-LD* case study less than 400 m from Natura 2000 and in region of 2–3 pig farms per hectare, *N-HD* case study less than 400 m from Natura 2000 and in region of 7–9 pig farms per hectare, *LD* case study further than 2 km from Natura 2000 and in region of 2–3 pig farms per hectare, *HD* case study further than 2 km from Natura 2000 and in region of 7–9 pig farms per hectare

annualised estimates of runoff from soils, terrestrial coverage and soil type for relevant areas and estimates of retention through absorption by soil particles, organism uptake and other biochemical processes (Helmes et al. 2012; Roy et al. 2014a; Henryson et al. 2018). We also used the CML Baseline v3.05 calculation method to estimate *non-renewable resource use* (NRRU) expressed in kg of antimony (Sb) equivalents, *non-renewable energy use* (NREU) expressed in mega-joules (MJ) and *global warming potential* (GWP) expressed in kg of carbon dioxide (CO_2) equivalents. The CML Baseline method does not account for spatial variability in fate factors for the receiving environment (i.e. soil-specific factors) in the assessment of GWP, NRRU and NREU. Each environmental impact category was assessed individually in this analysis, as we did not aggregate across categories.

A Monte Carlo (MC) method (1000 iterations) was used for the quantification of uncertainties related to data inputs and to distinguish between uncertainties specific to each scenario or shared between scenarios (Mackenzie et al. 2015; Pexas et al. 2020b). Statistical significance of differences when comparing between scenarios were evaluated using the 90% confidence intervals based on the sampled mean and standard deviation (1000 Monte Carlo iterations). Whenever uncertainty information was not available for variables relevant to any of the scenarios, we assumed that the variable was normally distributed with a standard deviation equal to 10% of the mean (Groen et al. 2014). We estimated the abatement potential of an alternative strategy as its difference in environmental impact for each individual category when compared to the baseline.

2.5 Economic model

The economic performance of the pig farming system with the implementation of each manure management strategy was evaluated through a discounted cash flow analysis over a 25-year time horizon (Pexas et al. 2020a). This approach was consistent with the life cycle cost analysis method, although due to data limitations, we assumed a zero end-of-life disposal value of capital equipment (Norris 2001). A comprehensive list of economic data was compiled by SEGES, to describe all relevant processes. Table 2 summarizes the main costs associated with the implementation of each manure management scenario. We assumed a standard deviation equal to 10% of the mean price reported whenever data was insufficient to account for variability in time. For the analysis, we used a long-term investment discount rate of 2.83% (Pexas et al. 2020a).

Capital costs were calculated and amortised over a 25-year lifetime for building-related components and a 12.5-year lifetime for technological equipment. Technological reinvestments were considered for equipment that was expected to be renewed at intervals more frequent than the time horizon. Costs related to the pig housing (i.e. building infrastructure, climate control, feed and water delivery and slurry removal technological equipment) and manure management component (i.e. slurry storage and field application equipment) were considered. Working capital included the purchasing of breeding stock.

Operational expenses included animal, pig housing management and manure management–related costs. Specifically, they included feed, veterinary/medical inputs, electricity and diesel fuel, technological equipment maintenance and labour. We accounted for variability in costs associated with the transportation and application of manure that had been treated with any of the alternative manure management strategies considered.

Total revenues consisted of live weight pig meat sold and avoided costs of synthetic fertiliser at crop production replaced by the field application of manure.

Two farm financial metrics commonly used to compare the economic performance of alternative investments were employed for the assessment of investment feasibility in the different location scenarios. Whole-farm annual equivalent value (AEV) was used as a measure of the annualised monetary returns and a proxy to estimate annual farm profitability (Eq. 1). AEV converts the net present value of a farming business to an annuity equivalent that is easier to interpret relative to the standard annual farm income, therefore facilitating more intuitive comparisons of the financial returns between investments of different scales. The second was the internal rate of return (IRR), which represents an investment's expected percentage return on capital over the time horizon.

$$\mathrm{AE}V = \frac{d(\mathrm{NP}V)}{1 - (1 + d)^{t}} \tag{1}$$

where d = discount rate, t = total number of years in time horizon, NPV = farm net present value calculated through the discounted cash flow.

2.6 Cost-effectiveness assessment

Upon estimation of the annualised system environmental and economic impacts, the cost-effectiveness of each manure management strategy was calculated separately for the different environmental impact categories considered through Eq. 2. Figure 1 provides a schematic representation of how the environmental LCA, economic model and spatial information connect within the spatially explicit cost-effectiveness framework.

$$\text{€}\, per\ unit\ of\ pollutant\ abated = \frac{\Delta AEV}{\Delta EI} \times (-1) \tag{2}$$

where ΔAEV = difference in whole-farm annual equivalent value between baseline and alternative manure management strategies and ΔEI = difference in environmental impact between baseline and alternative manure management strategy.

3 Results and discussion

3.1 Manure management strategies and manure chemical composition

Prior to the environmental LCA and economic assessment, the amounts of nitrogen and phosphorus available for field application annually were estimated for each manure management strategy considered. Under baseline conditions, a total of approximately 26,664 kg N year^{-1} and 8149 kg P year^{-1} were available for application as organic fertiliser. Anaerobic digestion of slurry resulted in an enriched digestate with higher nutrient concentrations of 47,490 kg N year^{-1} and 8413 kg P year^{-1}. When slurry was acidified, the resulting manure also contained higher amounts of nitrogen than the baseline scenario at 36,950 kg N year^{-1} and 8149 kg P year^{-1}. Finally, when screw press separation was implemented, the total amount of nitrogen available for application reduced at 22,520 kg N year^{-1} and 8149 kg P year^{-1}. The large differences in nitrogen concentrations of manure between the various manure management strategies were observed due to the different mitigation potential achieved for nitrogen-related emissions by each strategy. Anaerobic digestion and slurry acidification significantly abated ammonia, dinitrogen monoxide and nitrogen emissions at pig housing and manure storage, and therefore resulted to higher amounts of nitrogen in manure. Phosphorus concentration in manure was only affected with the implementation of anaerobic digestion, where it increased as a consequence of the co-digestion with grass silage process. While slurry separation allows for nutrient redistribution, the amount of total phosphorus at the end of the process is the same as prior its implementation.

We estimated arable land requirements for manure application under Danish legislation (170 kg N ha^{-1} year^{-1} and 35 kg P ha^{-1} year^{-1}), considering the amount of N and P produced by each manure management strategy as presented above. In cases N-LD and LD, we found that 157 ha was required for application of manure treated under the baseline strategy, 279 ha for the application of digestate, 217 ha for acidified manure and 133 ha for separated manure. In regions with 7–9 pig farms ha^{-1} (cases HD and N-HD) where we assumed that land was shared between three pig farms, requirements for available land were higher at 471 ha for baseline manure management, 839 ha with anaerobic digestion, 653 ha with slurry acidification and 398 ha with screw press slurry separation. The spatial analysis showed that in N-LD, a 9-km transportation distance of manure, was sufficient to meet the arable land requirements for baseline manure management and screw press separation and 10 km for the anaerobic digestion and slurry acidification strategies. In HD, the required transportation distance was 5 km for the baseline and screw press separation strategies, 6 km for slurry acidification and 8 km for anaerobic digestion. In LD, manure was applied within a 5-km radius with the implementation of any of the manure management strategies. Finally, in N-HD manure, transportation distance increased at 15 km under baseline and screw press separation strategies and 17 km if slurry acidification or anaerobic digestion was implemented. These outcomes reflect variability in land cover types (e.g. arable land, urban surface) of areas surrounding the pig farming system across different localities. Even in a topographically homogeneous country such as Denmark, we observed large differences in the percentage of area covered by arable land between the four geographic case studies tested (see Electronic Supplementary Material – ESM_1 Table S3.1). Such differences could be even more relevant in larger countries with greater topographic variability.

The maximum nitrogen deposition allowance in Natura 2000 areas is below 0.2 kg ha^{-1} year^{-1} pig farm^{-1} in cases where more than one neighbouring farms are located within 1 km from the system under assessment and below 0.7 kg ha^{-1} year^{-1} if there are no neighbouring farms (Jacobsen and Ståhl 2018; Jacobsen et al. 2019). While we considered this in our study, it did not lead to any significant differences in manure application–related environmental or economic impacts. Even when a pig farm was located amidst a large Natura 2000 network and in a region of 2–3 pig farms ha^{-1} (i.e. N-LD), the nitrogen deposition allowance did not result in any reductions in the required manure transportation distance.

3.2 Environmental life cycle assessment

Figure 3a–h present the annualised system environmental impact under baseline manure management and with the implementation of the alternative strategies considered, across the four geographic case studies and for each impact category separately. Table S3.2 of the Electronic Supplementary Material summarises the mean environmental impact of each scenario for the impact categories assessed and presents the 90% confidence intervals for each output to facilitate comparisons between the different scenarios.

3.2.1 Manure management strategies

When compared to the baseline manure management scenario, anaerobic digestion exhibited significant potential to mitigate system environmental impact for several impact categories, which varied across the four geographic locations tested. The abatement potential achieved for TAP by this strategy was 61.9% in N-HD ($p < 0.05$), 62.1% N-LD ($p < 0.05$) and HD ($p < 0.05$) and 65.5% in LD ($p < 0.05$). For NREU, it exhibited 29.2% abatement potential in N-HD ($p < 0.05$) and 30.1% in N-LD ($p < 0.05$), LD

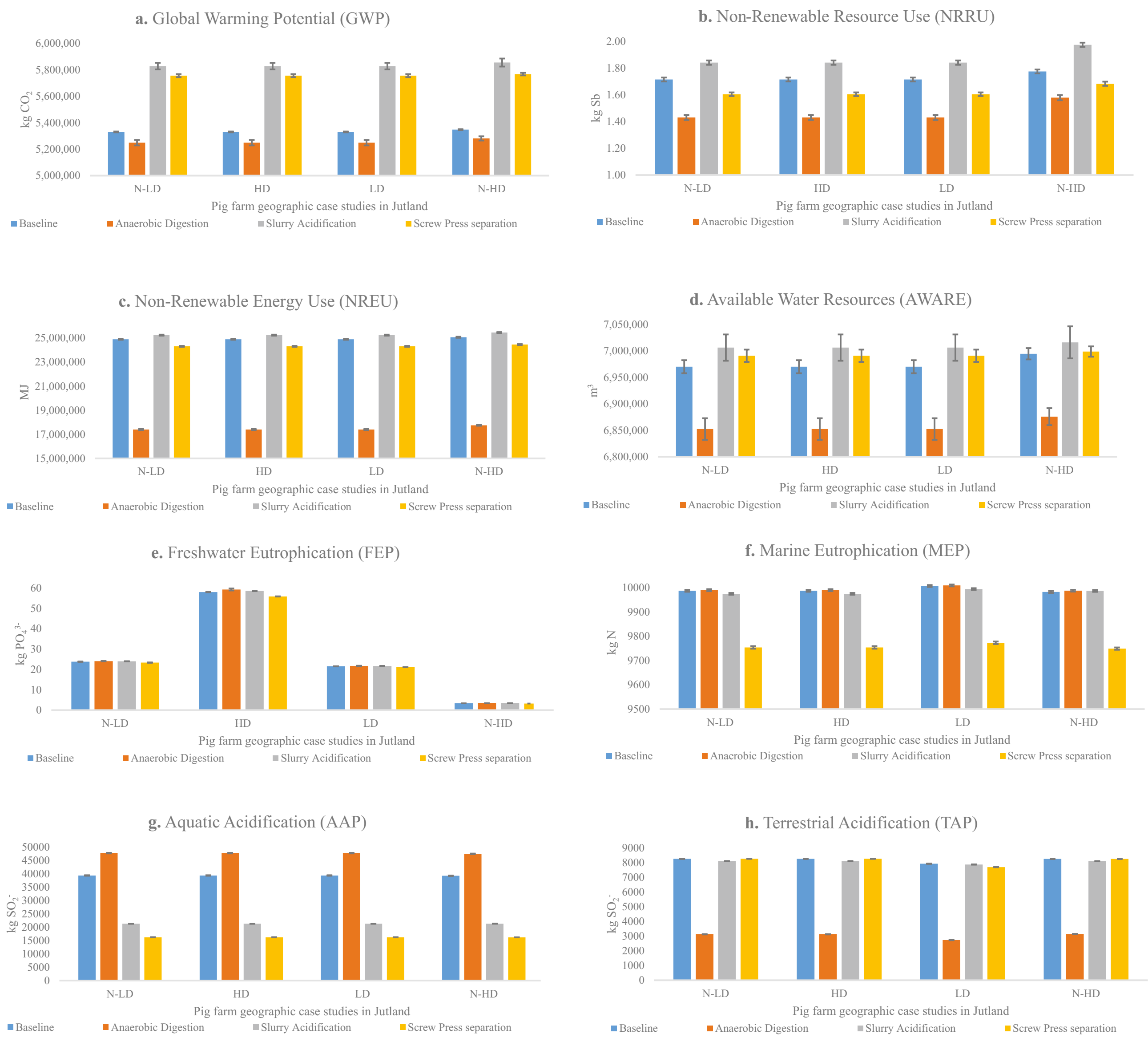


Fig. 3 **a–h** Annual system environmental impact under baseline manure management and with the implementation of three alternative manure management practices (anaerobic digestion, slurry acidification and screw press slurry separation), across four different geographic case studies in Jutland, Denmark. *N-LD* Case study less than 400 m from Natura 2000 and in region of 2–3 pig farms per hectare, *N-HD* Case study less than 400 m from Natura 2000 and in region of 7–9 pig farms per hectare, *LD* Case study further than 2 km from Natura 2000 and in region of 2–3 pig farms per hectare, *HD* Case study further than 2 km from Natura 2000 and in region of 7–9 pig farms per hectare

Table 1 Spatially explicit characterisation factors for the assessment of aquatic acidification potential, terrestrial acidification potential, freshwater eutrophication potential, marine eutrophication potential and available water resources. The characterisation factors were obtained from the IMPACT World + project (Bulle et al. 2019). The impact category and the substance contributing to it are presented for geographic case studies of pig production in Denmark

Impact category—substance	Unit	N-LD	N-HD	LD	HD
Aquatic acidification—nitric acid	kg SO2− eq	$1.14e^{-06}$	$1.14e^{-06}$	$7.54e^{-08}$	$1.14e^{-06}$
Aquatic acidification—nitrogen oxides	kg SO2− eq	$1.56e^{-06}$	$1.56e^{-06}$	$1.03e^{-07}$	$1.56e^{-06}$
Aquatic acidification—ammonia	kg SO2− eq	$5.64e^{-06}$	$5.64e^{-06}$	$1.73e^{-07}$	$5.64e^{-06}$
Aquatic acidification—sulphur dioxide	kg SO2− eq	$4.37e^{-06}$	$4.37e^{-06}$	$1.65e^{-07}$	$4.37e^{-06}$
Terrestrial acidification—sulphur dioxide	kg SO2− eq	0.00616	0.00616	0.000734	0.00616
Terrestrial acidification—nitrogen oxides	kg SO2− eq	0.00192	0.00192	0.000341	0.00192
Terrestrial acidification—ammonia	kg SO2− eq	0.0151	0.0151	0.000749	0.0151
Freshwater eutrophication—phosphorus	kg PO43− eq	0.00856	0.000797	0.00774	0.00999
Freshwater eutrophication—phosphate	kg PO43− eq	0.00280	0.000261	0.00253	0.0326
Marine eutrophication—nitrogen oxides	kg N eq. kg−1	0.0530	0.0530	0.0524	0.0530
Marine eutrophication—ammonia	kg N eq. kg−1	0.226	0.226	0.449	0.226
Available water resources—water use	m3 world eq	0.880	0.494	2.27	0.768

N-LD case study less than 400 m from Natura 2000 and in region of 2–3 pig farms per hectare, *N-HD* case study less than 400 m from Natura 2000 and in region of 7–9 pig farms per hectare, *LD* case study further than 2 km from Natura 2000 and in region of 2–3 pig farms per hectare, *HD* case study further than 2 km from Natura 2000 and in region of 7–9 pig farms per hectare

($p < 0.05$) and HD ($p < 0.05$). The opposite trend was observed for AAP (+ 20.9% to + 21.3%) where anaerobic digestion was the worst manure management scenario overall, with 20.9% higher impact in N-HD ($p < 0.1$) and 21.3% in N-LD ($p < 0.1$), LD ($p < 0.1$) and HD ($p < 0.1$), compared to the baseline manure management. No difference was observed in environmental performance for GWP, AWARE, NRRU, FEP and MEP between this strategy and the baseline ($p > 0.1$).

The implementation of screw press separation resulted in the largest reductions ($p < 0.05$) overall for AAP (58.8% in N-HD and 58.4% in N-LD, LD and HD). This manure management scenario performed worse ($p < 0.05$) than the baseline for GWP (7.84% in N-HD and 7.97% in the other locations), while we did not observe any differences in environmental performance for NRRU, MEP and AWARE ($p > 0.1$).

The largest, abatement potential of the slurry acidification strategy was observed for AAP (45.7% in N-HD and 45.9% in all other locations) compared to the baseline ($p < 0.05$). Under this manure management scenario, we observed the worst system environmental performance overall for GWP with + 9.48% in N-HD ($p < 0.05$) and 9.33% in the rest of case studies ($p < 0.05$). No differences were observed between the baseline scenario and slurry acidification for NREU, NRRU, FEP, TAP, MEP and AWARE.

The outcomes of the environmental impact assessment for the different manure management scenarios were according

Table 2 Main costs of categories associated with the implementation of the baseline and alternative manure management strategies on a typical integrated Danish pig farm Source: Pexas et al. (2020a)

Cost category	Unit	Cost
Diesel fuel	€ per litre	1.35
Electricity from the national grid-household price	€ per kWh	0.100
Electricity from natural gas	€ per kWh	0.0912
Labour, wage	€ per hour	22.5
Acidification plant (incl. pumping system)	€ per unit	16,495
Sulphuric acid 96% (H_2SO_4) per kg	€ per kg	0.0673
Calcium carbonate ($CaCO_3$)	€ per kg	0.102
Total on-farm AD project costs (incl. connection to grid & other fees)	€ per unit	556,833
Total on-farm AD operating expenses (incl. labour, co-substrate, maintenance)	€ per m^3 manure treated	14.2
Screw press separator (incl. mixer, separator, controls, pumping system)	€ per unit	36,913
Manure application with broadband spreading and rapid incorporation	€ per m^3 manure	2.00

AD anaerobic digestion

to our expectations (Pexas et al. 2020a; 2020b). Anaerobic digestion consists of complex processes that lead to the generation of electricity and heat, which is used on-farm to reduce energy consumption at various stages of the operation of the pig production system, and therefore mitigate system carbon footprint (−3.17% for GWP compared to the BAU scenario) and the potential for depletion of fossil fuel (−33.5% for NREU compared to the BAU scenario) (Cherubini et al. 2015; Pexas et al. 2020b). Besides these environmental benefits, the co-digestion process returns a nutrient-enriched digestate that although more efficient as fertiliser than untreated manure can intensify acidification (terrestrial and aquatic) and eutrophication-related problems (Vega et al. 2014).

Separation of slurry by screw press is a popular manure management strategy used to facilitate nutrient re-distribution through the storage and application of the liquid and solid fractions of slurry by different methods, i.e. storage of solid fraction in piles and broadcast spreading with rapid incorporation at field (Ten Hoeve et al. 2014). Because of such differences, nitrogen related emissions can be affected with the implementation of slurry separation, particularly when these are combined with good agricultural practices at the relevant stages, for example covering of the solid fraction piles to further reduce ammonia emissions (Ten Hoeve et al. 2016).

Slurry acidification significantly reduced system environmental impact for categories that are largely affected by nitrogen-related emissions, such as the acidification potential. Slurry acidification is commonly implemented in the larger pig farming systems of Denmark, to help reduce ammonia emissions at pig housing, manure storage and field application. However, the use of highly concentrated sulphuric acid and energy required for the processes of mixing and pumping may result in noticeable increases in system environmental impact for the GWP, NRRU and NREU categories (Kai et al. 2008; Fangueiro et al. 2015). We acknowledge that throughout the process of slurry acidification, many volatile sulphuric components can be formed that have potential adverse effects on the animals and the environment (Borst 2001), which were not accounted for in this study. The addition of calcium carbonate at field application helps mitigate some of these negative acidic effects but also increases system environmental impact for the NRRU category (Saue and Tamm 2018).

3.2.2 Effect of location on environmental impact of manure management strategies

In many cases, the spatially explicit environmental life cycle analysis revealed noticeable effects of location on system environmental impact, however not statistically significant at $a = 10\%$. System environmental impact under baseline manure management exhibited potential increases by +0.326% for GWP, +0.685% for NREU and +3.50% for NRRU for each of the above categories respectively in N-HD compared to the other geographic case studies. Baseline manure management was the least sensitive scenario for these impact categories, to geographic variability. With screw press separation, we observed a potential for higher system environmental impact by +0.195% for GWP, +0.613% for NREU and +4.90% for NRRU. Slurry acidification exhibited a potential +0.463% increase for GWP, +0.857% for NREU and +7.23% for NRRU. Finally, system performance for the above impact categories was mostly affected by geographic variability when anaerobic digestion was implemented, where we noted a potential increase of +0.613% for GWP, +2.02% for NREU and +10.4% for NRRU in N-HD than in the other geographic case studies.

GWP, NRRU and NREU are largely affected by energy consumption at various stages of production, and fuel consumption for manure transportation is an important source of emissions related to such impacts (Lammers et al. 2010; Pexas et al. 2020b). Therefore, as arable land availability and manure transportation distances change across different geographic case studies, so does system environmental performance in relation to the above impact categories. While in cases N-LD and LD transporting manure at a distance of 10 km met the requirements for application under Danish legislation, in N-HD, the farmer needed to travel longer distances (up to 17 km) to reach the required arable land.

Under baseline manure management, system performance for AWARE was also noticeably worse in N-HD (~+0.350%) than in any other geographic case study, but not significantly different at $a = 10\%$. When alternative manure management strategies were implemented, we did not observe any sizeable effects of location on system performance for AWARE. This could be attributed to that the large uncertainties associated with the calculation of this impact category, particularly when assessing such complex processes, outweighed any observed difference in the specific results. Two main factors are involved in the characterisation of issues related to water availability and the depletion of available water resources: (i) human demand for water resources, which is represented by data on current water consumption and includes use by the domestic, industrial, agricultural, livestock and energy production sectors, and (ii) ecosystem demand for water resources, which is represented by environmental water requirements (i.e. minimal flow of water required) to maintain freshwater ecosystems in "fair" ecological state (Boulay et al. 2018). Eliminating uncertainties around such a multidimensional impact category is critical in enhancing accuracy of future assessments and allowing LCA practitioners to identify the specific factors responsible for the large variabilities exhibited in AWARE.

Differences were observed for FEP, which exhibited the largest spatial variability in system environmental performance. With the implementation of anaerobic digestion in HD, system impact was 16.5 times higher (59.3 kg PO_4^{3-} eq. year^{-1}) than in N-HD (3.38 kg PO_4^{3-} eq. year^{-1}) ($p < 0.05$). In addition, we observed that relative performance differences between the various manure management scenarios were larger in HD than in other geographic case studies. For instance, screw press slurry separation exhibited 6.13% lower FEP than anaerobic digestion in HD but only 4.56% lower in N-HD and an even smaller difference of 3.02% lower impact in cases N-LD and LD. A number of factors may explain the variability observed across the different locations tested in this study, in the characterisation of FEP. A main factor is the persistence of phosphorus in freshwater ecosystems, which is largely affected by the rate of phosphorus removal from the receiving environment through the advective flow of water, the uptake by biomass, its absorption to suspended solids and subsequent settling and removal through water use for agricultural purposes (irrigation). Noticeable changes in these factors and practices between locations may result in sizeable effects of geography on the environmental impact of a farming system.

We did not find differences in system performance between cases N-LD, HD and N-HD, under any of the manure management scenarios for MEP ($p > 0.1$).

A similar pattern was observed for TAP, with no differences between the geographic cases ($p > 0.1$), but with system performance being noticeably lower in LD than in the other locations tested. Observed differences ranged between −3.98 and −4.03% under baseline manure management, −12.6 and −13.0% with anaerobic digestion, −2.85 with slurry acidification and −6.78 and −6.90% with screw press separation for this impact category.

Finally, we did not observe changes in AAP when anaerobic digestion was implemented, where system performance was lower in N-HD (−0.598 to −0.599%, $p > 0.1$) than the other geographic case studies.

The manure management strategies evaluated in our study all greatly affect airborne, waterborne and emissions to the soil that largely contribute to impacts on ecosystem quality; they do so in diverse ways from one another (Ten Hoeve et al. 2014; Ten Hoeve et al. 2016; Pexas et al. 2020b). Using spatially explicit characterisation factors for most emissions affected by these strategies (Roy et al. 2014b; Henryson et al. 2018), we have highlighted sizeable and in many cases statistically significant spatial effects on system environmental performance for impacts on ecosystem quality, including freshwater and marine eutrophication, and terrestrial and aquatic acidification. The observed differences in environmental performance between geographic locations respond to the effects of topographic and climatic variability on emission transportation and fate (Bulle et al. 2019).

3.3 Economic performance and cost-effectiveness of manure management strategies

Table 3 presents the whole-farm annual equivalent value and internal rate of return for all manure management strategies when implemented in the four different geographic locations. Our findings suggest that farm profitability is largely affected not only by the choice of manure management strategy but also geography. In the N-LD geographic case, anaerobic digestion was 22.2% more profitable (higher annual equivalent value) than the baseline manure management. With the implementation of screw press slurry separation, the farm was 9.05% less profitable, and when slurry acidification was implemented, the farm performed even worse financially, exhibiting 79.8% lower AEV than the baseline. We observed a similar trend in the N-HD case study but with the observed differences greatly enlarged in comparison to N-LD. Specifically, when anaerobic digestion was implemented in N-HD, farm profitability was 3.68 times higher than the baseline scenario in this location. In the same geographic case study, screw press separation and slurry acidification performed worse than the baseline scenario by 48.2% and 534% respectively. In cases LD and HD, baseline manure management was the most profitable scenario overall. In both those geographic cases, screw press

Table 3 Whole-farm annual equivalent value (AEV) and internal rate of return (IRR) under baseline manure management and with the implementation of three alternative manure management strategies across the four geographic case studies

Farm location	Baseline		Anaerobic digestion		Slurry acidification		Screw press separation	
	AEV (€)	IRR (%)	AEV (€)	IRR (%)	AEV (€)	IRR (%)	AEV (€)	IRR (%)
N-LD	34,427	6.01	42,073	5.75	6,956	3.50	31,312	5.68
HD	52,793	7.59	44,048	5.88	20,731	4.77	49,811	7.25
LD	52,793	7.59	47,341	6.10	25,322	5.18	49,811	7.25
N-HD	6878	3.50	32,196	5.10	−29,776	0.271	3564	3.17

N.A not applicable, *N-LD* case study less than 400 m from Natura 2000 and in region of 2–3 pig farms per hectare, *N-HD* case study less than 400 m from Natura 2000 and in region of 7–9 pig farms per hectare, *LD* case study further than 2 km from Natura 2000 and in region of 2–3 pig farms per hectare, *HD* case study further than 2 km from Natura 2000 and in region of 7–9 pig farms per hectare separation performed second best resulting in 5.65% lower whole-farm annual equivalent value than the baseline. With the implementation of anaerobic digestion in LD, farm profitability was 10.3% lower than the baseline manure management scenario and 16.6% lower when it was implemented in HD. Finally, when slurry acidification was implemented in LD and HD, whole-farm AEV was 52.0% and 60.7% lower than the baseline scenario in each of the geographic cases respectively.

Table 4 summarises the cost of abatement associated with mitigation of each impact category by the three alternative manure management strategies across the four geographic locations considered. Anaerobic digestion was the only manure management strategy to increase profits while reducing the system environmental impact for GWP, NRRU, NREU, TAP and AWARE. The cost-effectiveness of anaerobic digestion improved when the strategy was implemented in N-HD compared to other geographic locations. The largest differences were observed between N-HD and HD with cost-effectiveness being 4.55 times higher in the former for GWP, 5.20 times for NRRU, 3.96 times for NREU, 3.91 times for TAP and 3.87 times higher for AWARE. Despite achieving substantial abatement potential for several impacts, both slurry acidification and screw press separation incurred additional costs for the abatement of any impact category assessed. For the common categories they mitigated, screw press separation was overall the more cost-effective option, due to its lower cost of implementation and shorter distance required for manure application when compared to slurry acidification. The cost-effectiveness of both slurry acidification and screw press separation exhibited large geographic variability for the various impact categories they mitigated, which reflects the spatial variability in their abatement potential as well as differences in availability of arable land for manure application between the geographic case studies. Overall, both strategies performed the worst for N-HD. With the implementation of screw press separation, the largest geographic difference was found between N-HD and LD, where the cost of abatement for TAP was 162 times higher in N-HD. Cost of abatement was also higher in N-HD for the mitigation of FEP with the largest difference being 19.3 times higher than in HD, NRRU (33.4% higher than HD, LD), AAP (11.6% higher than HD,LD), MEP (10.9% higher than HD,LD) and NREU (7.09% higher than HD,LD). The largest spatial difference in cost-effectiveness of slurry acidification was observed between LD and N-LD for the mitigation of TAP, where it incurred 1.80 times higher additional costs in LD. For AAP, cost of abatement was higher in N-HD than in HD, LD by 34.9%, and for MEP higher in HD than LD by 17.1%.

While profitable overall, on-farm anaerobic digestion is a large investment especially for a medium-sized farm (500-sow integrated pig farm) (Nolan et al. 2012; Pexas et al. 2020a). However, it results in large on-farm energy discounts with the generation of electricity and heat from manure. Furthermore, it returns a nutrient-enriched digestate with improved fertilising properties that translate to sizeable discounts in synthetic fertiliser use (Nolan et al. 2012; Vega

Table 4 Cost of abatement of the alternative manure management strategies considered for mitigation of each impact category assessed and across the four geographic case studies, expressed in euro per unit of pollutant abated. Negative (−) costs indicate that profit was generated along with environmental impact abatement

Cost of abatement per impact category	Manure management strategy	N-LD	HD	LD	N-HD
Global warming potential (€/kg CO_2 eq.)	Anaerobic digestion	−0.0939	0.107	0.0670	−0.380
Non-renewable resource use (€/kg Sb eq.)	Anaerobic digestion	−26,907	+30,775	+19,186	−129,374
	Screw press separation	+28,242	+27,036	+27,036	+36,066
Non-renewable energy use (€/MJ)	Anaerobic digestion	−0.00102	+0.00117	+0.000727	−0.00346
	Screw press separation	+0.00531	+0.00508	+0.00508	+0.00544
Available water resources—AWARE (€/m^3)	Anaerobic digestion	−0.0650	+0.0743	+0.0463	−0.213
Freshwater eutrophication (€/kg PO_4^{3-} eq.)	Screw press separation	+6,822	+1,388	+7,225	+28,229
Marine eutrophication (€/kg PO_4^{3-} eq.)	Slurry acidification	+2,189	+2,554	+2,181	N.A
	Screw press separation	+13.4	+12.8	+12.8	+14.2
Aquatic acidification (€/kg SO_2^- eq.)	Slurry acidification	+1.52	+1.78	+1.52	+2.05
	Screw press separation	+0.135	+0.129	+0.129	+0.144
Terrestrial acidification (€/kg SO_2^- eq.)	Anaerobic digestion	−1.49	+1.70	+1.05	−4.95
	Slurry acidification	+173	+202	+484	+236
	Screw Press separation	N.A	N.A	+12.9	+2,111

N.A no abatement, *N-LD* case study less than 400 m from Natura 2000 in region of 2–3 pig farms per hectare, *N-LD* case study less than 400 m from Natura 2000 and in region of 2–3 pig farms per hectare, *N-HD* case study less than 400 m from Natura 2000 and in region of 7–9 pig farms per hectare, *LD* case study further than 2 km from Natura 2000 and in region of 2–3 pig farms per hectare, *HD* case study further than 2 km from Natura 2000 and in region of 7–9 pig farms per hectare et al. 2014; Cherubini et al. 2015). In geographic cases with limited availability of arable land, additional manure transportation costs incurred due to the increased nutrient load of the digestate compared to untreated manure may worsen the strategy's economic performance and render it less profitable than other potential manure management options. This effect was observed in geographic case HD, where due to a 3-km increase in manure transportation distance compared to the baseline and slurry separation scenarios, anaerobic digestion performed financially worse than both. In contrast to our expectations (Pexas et al. 2020a), in geographic case LD where manure transportation distance was the same (5 km) for all manure management scenarios, on-farm anaerobic digestion also performed worse than the baseline and slurry separation scenarios, which reveals important effects of manure transportation distance on farm profitability. Overall, anaerobic digestion was less sensitive to changes in manure transportation distance when compared to other manure management scenarios (including the baseline), due to the increased revenues from energy-related and fertiliser-related cost discounts associated with its implementation that acted as counterpoints. Such interactions could explain the geographic variability in cost-effectiveness of the strategy to mitigate various environmental impacts, which is a function of the difference in AEV between the strategy and the baseline. AEV differences between anaerobic digestion and the baseline outweighed the respective differences in environmental impact across all geographic locations. These findings enhance the relevance of even basic spatially explicit information with potential economic implications, such as availability of land for manure application, to be integrated in the assessment of cost-effectiveness for alternative manure management strategies. As mentioned previously, anaerobic digestion is a complex scenario involving several parameters the variability of which we could not capture in our study. However, we acknowledge that the accuracy of the spatially explicit cost-effectiveness assessment of this strategy could be enhanced further with the consideration of geographic variability in the specific power mix used by and discounted on the farming system, as well as the price and properties of the co-substrate used.

Slurry acidification is also a large investment with high capital and operating expenses (Kai et al. 2008; Fangueiro et al. 2015). While in this study we have considered the addition of sulphuric acid as the acidifying agent, we acknowledge that other substances may be able to achieve comparable mitigation of ammonia emissions at a lower cost (Saue and Tamm 2018). Due to large ammonia emissions reductions achieved at pig housing and manure storage by this strategy, more land would be required for the nitrogen-rich acidified slurry to be applied, therefore increasing manure transportation costs and further reducing farm profitability. According to our analysis, 1 km increase in manure transportation distance incurred ~ €4591 (~€0.70 per m^3 of manure), which could explain the large differences observed in farm profitability and cost-effectiveness between the four geographic case studies considered. The observed spatial variability in cost-effectiveness of this manure management strategy could also be explained by geographic differences in abatement potential across the impact categories it mitigated. For impact categories and in geographic cases where the strategy achieved little abatement potential, its cost-effectiveness would be relatively poor, particularly if its economic performance was also poor compared to the baseline (e.g. implementation of slurry acidification in LD geographic case for mitigation of TAP).

Mechanical slurry separation is a common manure management practice in Danish pig farming systems, and screw press is amongst the most popular methods due to its relative low cost of implementation (Pexas et al. 2020a; Ten Hoeve et al. 2014). With slurry separation, most of the phosphorus ends up in the less voluminous solid fraction, which allows for better nutrient redistribution at field application and helps keep costs low if slurry exceeds the allowance for phosphorus and needs to be applied at longer distances (Ten Hoeve et al. 2014; F. Udesen, SEGES, personal communication, February 27, 2018). Similar to the case of slurry acidification, geographic variability in the economic performance and cost-effectiveness of screw press separation can be attributed largely to the observed differences in distance required for manure transportation and application. Another factor that contributed to the observed differences in financial performance between screw press separation and the baseline manure management strategy is the cost of application for the solid fraction of manure using broadcast spreading and rapid incorporation (€2.00 per m^3 of manure). This application method is approximately 25% as expensive as the baseline practice of application with trail-hose tanker (~ €1.6 per m^3 of manure) and applies to 37% of the total slurry produced, which corresponds to the extracted solid fraction after separation based on the separation efficiency for this specific technology (Ten Hoeve et al. 2014). While we recognise the potential for application of the two fractions in different locations might enhance farm economic performance particularly in areas where arable land is scarce (e.g. N-HD), in our study, we simulated field application regimes based only on land availability and specific Danish regulations. The inclusion of more precise spatially explicit information regarding the location where each fraction is applied, as well as relevant regional policies on nutrient deposition, could enhance accuracy when assessing the cost-effectiveness of this strategy.

In addition to the factors we considered for the spatially explicit cost-effectiveness analysis presented here, we also acknowledge that agglomeration effects can have a significant impact on the efficiency of a pig farming system, especially when considering the implementation of complex investments such as the manure management strategies evaluated here (Larue et al. 2011; Gaigné et al. 2012). While we did not simulate such effects due to lack of sufficient relevant data, we appreciate that as pig farming density increased so might technical efficiency, knowledge spill overs and potentially the availability of more specialised labour force (Larue et al. 2011). This improved farm efficiency could potentially facilitate the realisation and operation of large investments and counterbalance some of the additional costs incurred in dense areas (i.e. where HD and N-HD were located), enhancing farm profitability overall.

Furthermore, we are aware that near Danish Natura 2000 areas, legislation could enforce ceilings on ammonia emissions associated with animal stables and manure storage that in many cases might hinder the expansion of farming operations and therefore farm profitability (Jacobsen and Ståhl 2018; Jacobsen et al. 2019). Regional restrictions could alter farmer investment behaviour and shift their priorities from the most cost-effective option, towards technologies that primarily target mitigation of specific emissions in compliance with relevant agri-environmental policies (Sutherland 2010). Such a case could be that slurry acidification may be prioritised over anaerobic digestion to reduce ammonia emission at pig housing and slurry storage and allow the business to expand near sensitive habitats avoiding relocation.

3.4 Methodological implications and challenges

Within this case study, we showed that the incorporation of even relatively limited spatial data in livestock LCA models can significantly alter the outcomes of environmental abatement cost assessments, when evaluating investments that aim to improve sustainability of livestock farms. Without the spatially explicit data, all results would have been identical for the four geographic case studies tested with this farm-level LCA model. While in our study we present findings for the case of manure management for Danish pig farming operations, the method applied here would be useful when analysing the cost-effectiveness of on-farm investments for environmental impact abatement across the livestock sector, given the universal need to manage manure and reduce emissions associated with animal production.

The research presented here suggests there is room for further methodological improvements that can be achieved in exercises that address the cost-effectiveness of alternative manure management strategies in pig production systems. A potential avenue for improvement of the study would be to consider testing the framework in countries (case studies) that exhibit larger topographic and climatic variability across space than Denmark (Larue et al. 2011). Asides from topographic heterogeneity, a broader case study could also be more appropriate for investigating the potential effects of socio-economic factors on system sustainability. While in this paper we have accounted for nationwide relevant legislation, we acknowledge that more regionalised regulations are commonly enforced in countries with great diversity in social and economic factors across their spatial extent (Mishra et al. 2009).

In this study, we addressed each environmental impact category individually and did not aggregate across impact categories, in order to provide a more pragmatic option for the decision-making process. We acknowledge the existence of several weighting options, i.e. based on public opinion and monetary valuation, which may allow for the summary of indicators in a single eco-efficiency score (Bengtsson and Steen 2000; Soares et al. 2006). However, we consider the weighting of impacts a subject more appropriately addressed by decision makers in the application of the framework presented here, rather than the core focus of the present study.

Reducing uncertainties related to the calculation of specific environmental impact categories by improving the calculation methods and by using detailed, regionalised life cycle inventories could further enhance the discriminating power of such spatially explicit cost-effectiveness assessment frameworks (Bulle et al. 2019). In our study, we have identified the system water footprint (AWARE) as such a problem area, where large variability in the results as evident by the observed standard errors outweighed potential spatial effects (Fig. 3d).

While we have accounted for uncertainties inherent in the environmental life cycle assessment inventories and models by following well-established methods (Mackenzie et al. 2015), we could not account for uncertainties related to data that describe the system financial performance. This is a particularly difficult task to undertake in spatially explicit economic performance assessments at farm level (Rosenthal and Strange 2004). Examples of such uncertainties would be the potential geographic variability in prices for various inputs required for the construction and operation of the pig farming system in different geographic case studies (i.e. feed ingredients, construction material and wages). Spatial variations in input (output) prices can arise due to differences in supplier (buyer) concentrations and competitive intensity between regions. However, such differences are expected to be more prevalent in large countries, where spatial price variations usually reflect greater transportation distances to suppliers or markets. In the more compact geographic context of the present study, such factors are less consequential, therefore justifying our assumptions of uniformity in prices across the case study locations.

3.5 Policy implications

Our paper highlights the importance of accounting for spatial variability in system environmental impact and economic performance when evaluating the cost-effectiveness of strategies that aim to improve farm sustainability. The framework presented here offers opportunities to stakeholders for potential hotspot identification regarding harmful emission, capital and operating costs as well as revenue streams associated with operation of a farming system. In doing so, it enables farm managers to pinpoint areas of improvement and cost-effective strategies towards a more sustainable system. It is essential that producers evaluate their farming operations through such comprehensive environmental and socio-economic assessments, to fully understand the impacts and potential of their business as well as to guide decision-making for their improvement (Hellweg and Canals 2014; Liao et al. 2020).

Our results have broader implications in facilitating policy-making about the improved environmental and economic performance of various agricultural sectors and on a broader geographic extent. We have identified important trade-offs between the environmental impact categories considered, which relate so much to the choice of specific mitigation strategy as well as to the geographic location where this strategy would perform most effectively. In our analysis, we observed that more expensive investments were required to mitigate GWP, NRRU and NREU, and that such investments can be justified financially where legislation imposes strict restrictions on nutrient deposition through manure application. Policy-makers and other stakeholders that set specific environmental mitigation targets in each agricultural sector can use such information to guide investment strategies and meet their goals (Eory et al. 2018).

4 Conclusions

We presented an LCA-based spatially explicit, whole-farm, cost-effectiveness assessment framework that addressed the interactions between location-specific factors and potential farm investments that aim to improve pig farming system sustainability. The spatially explicit environmental life cycle analysis revealed significant effects of location on system environmental impact. We further showed a significant effect of location on the cost-effectiveness of all manure management strategies considered in mitigating several types of environmental impact. Anaerobic digestion was the only "win–win" manure management strategy that generated profit while improving system environmental performance for two of the geographic locations tested. Slurry acidification and screw press separation achieved sizeable abatement potential for impacts on ecosystem quality but incurred large additional costs in any of the geographic case studies considered, particularly when arable land was limited near the pig farm. The observed interactions between the cost-effectiveness of a potential farm investment and different geographic locations highlight the importance to account for spatial variability in environmental and economic impact assessments and reinforce the motivation to improve on relevant existing datasets by accounting for geographic uncertainties. The methodology has applications beyond the specific case study presented here, demonstrating the potential to integrate basic spatial data within farm-level LCA modelling of livestock systems to facilitate decision-making for the choice of investments that aim to improve system sustainability in a cost-effective manner.

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